*Modeling of Ion Beams for Fusion**

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Introduction

The VNL simulations & theory group has a broad charter

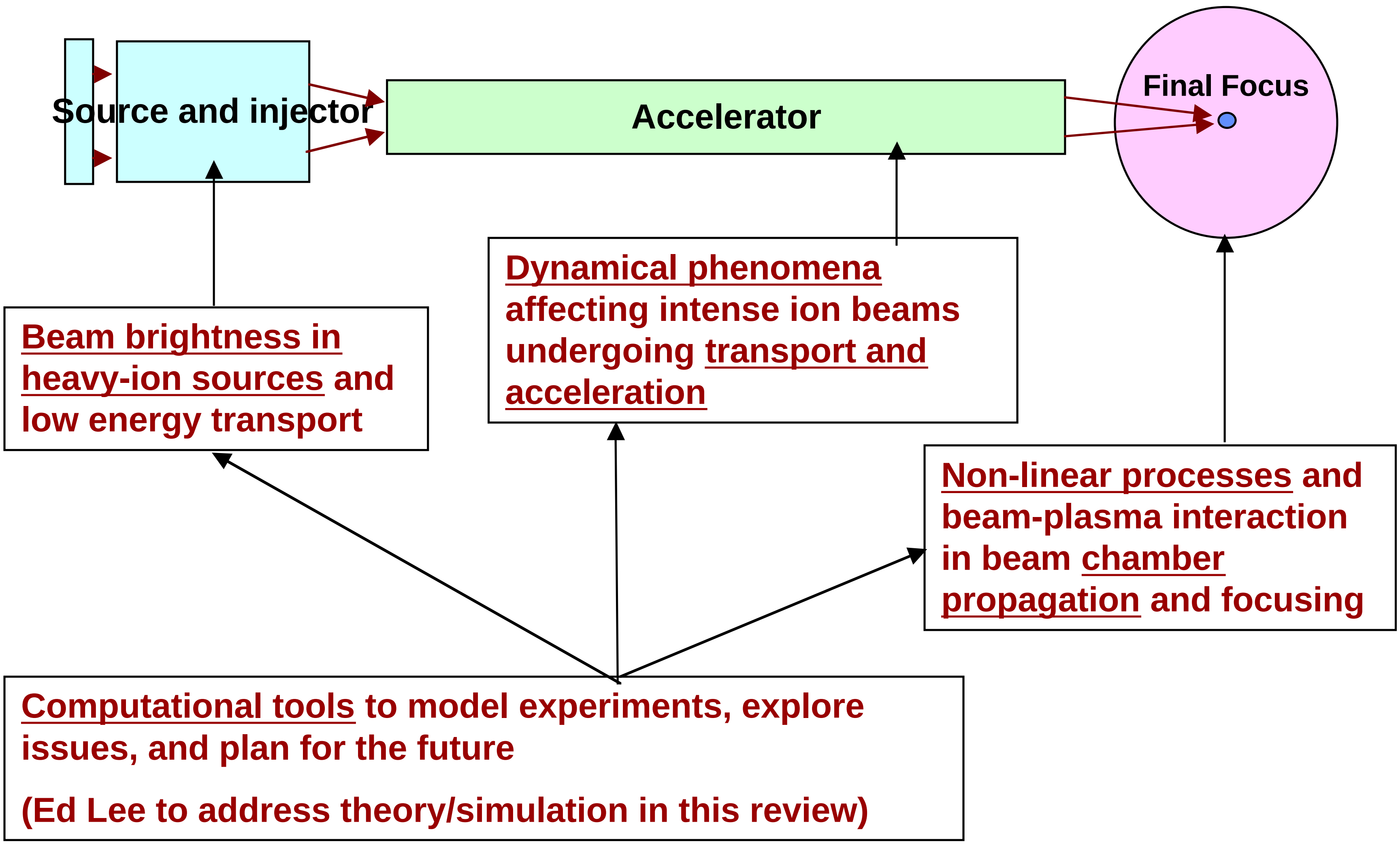
Development of the beam physics knowledge base
- key physics issues
- scaling laws

Laying the scientific foundation for future fusion accelerators

Planning and interpretation of experiments
- advanced injectors
- HCX
- focusing and chamber transport

Development of computational tools
- simulation codes
- systems code

HIF Scientific Issues



VNL simulation and theory concentrate on beam quality; 2002-2003 objectives with guidance funding

- **Simulation of HCX results: determine scaling laws for high current transport limits, halos, and heating**

- **3-d Computations of multi-beam dynamics: determine conditions for equilibrium, transverse and longitudinal stability; full scale and IRE scale machines**

- **Investigate electron cloud effects in beams transported by magnetic quadrupoles: determine the degree of electron trapping and multi-magnet effects**

- **Pulse compression and final focus: simulate strong chromatic effects and their control by pulsed focal elements. Produce a consistent accelerator-to- chamber model**

- **Chamber transport in neutralized ballistic mode: use LSP to simulate near-target pinch effects and the role of stripping to multiple charge states**

VNL simulation and theory concentrate on beam quality; 2002-2003 objectives with guidance funding (continued)

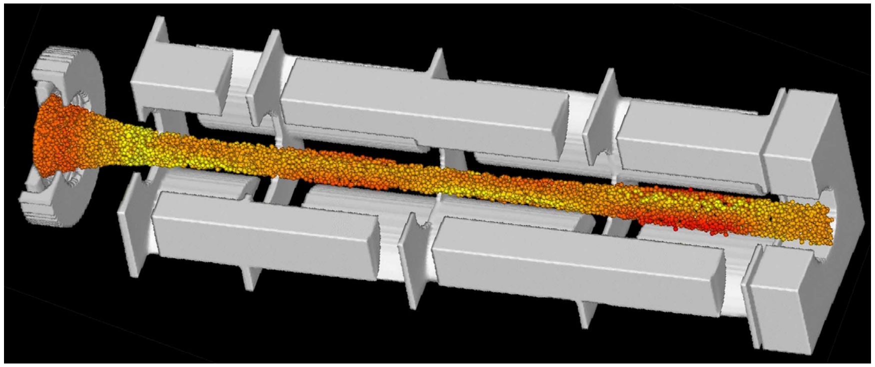
- **WARP 3-d development: incorporate adaptive mesh around multiple beams, and merge improved lower level codes**
- **BEST (δf) code development: complete optimization of parallelized version for study of two-stream interactions**
- **Benchmark chamber transport codes LSP and BPIC**

2002-2003 objectives with enhanced funding

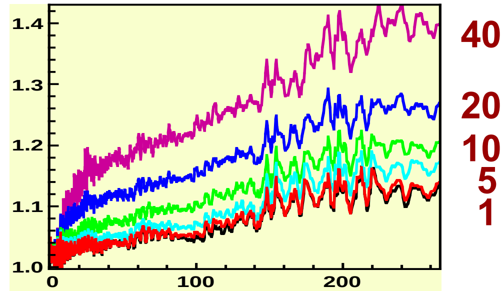
- Chamber transport in pinched mode: Simulation and theory model development of stability and pulse expansion with mobile plasma ions
- BEST code: Complete non-linear δf simulation of pressure anisotropy-driven instabilities in transported ion beams
- Electron cloud effects in a driver: add mobile plasma ions
- WARP code: incorporate Vlasov solver to efficiently treat low densities in phase space (e.g. halos)
- Chamber transport in neutralized ballistic mode: assess the two-stream and filamentation instabilities
- Neutralized high current final focus experiment: make simulation and analylical predictions and experimental comparisons.

Capabilities and Activities

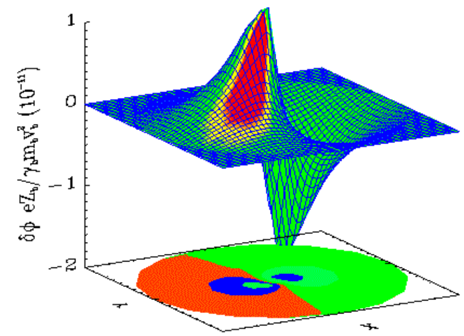
HIF beam simulations and theory span a variety of processes



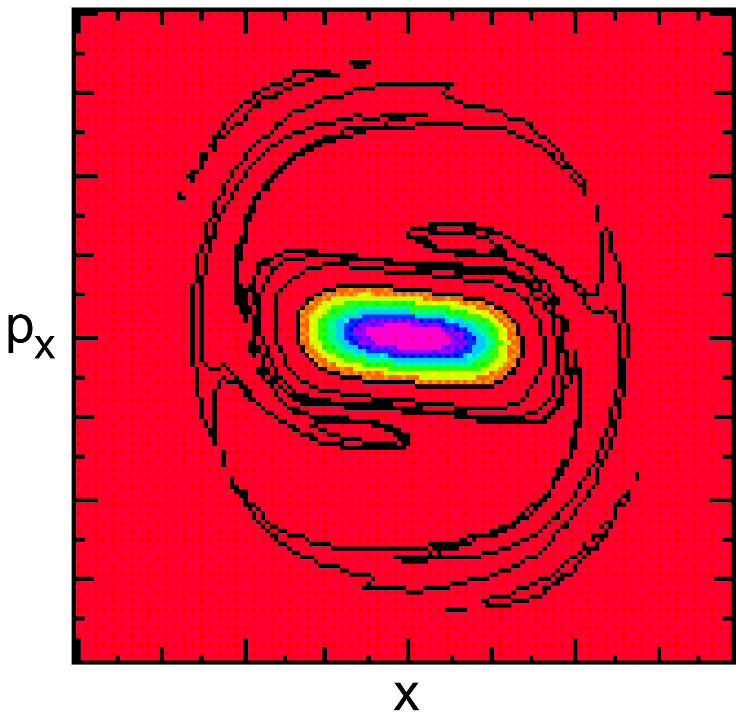
acceleration in 3-D structure



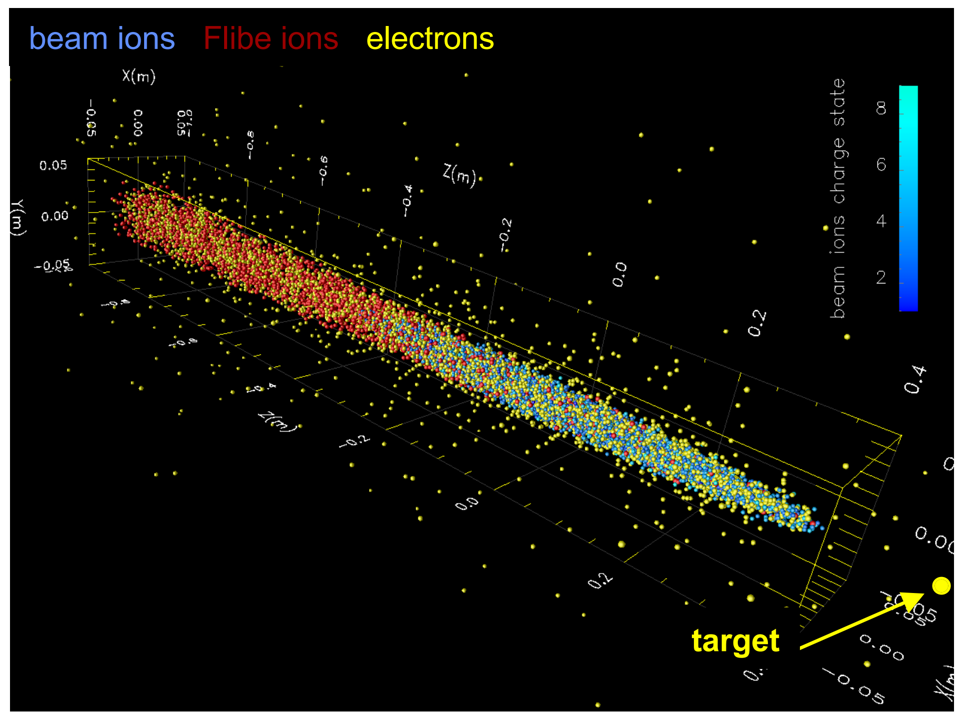
emittance growth and beam steering



instabilities

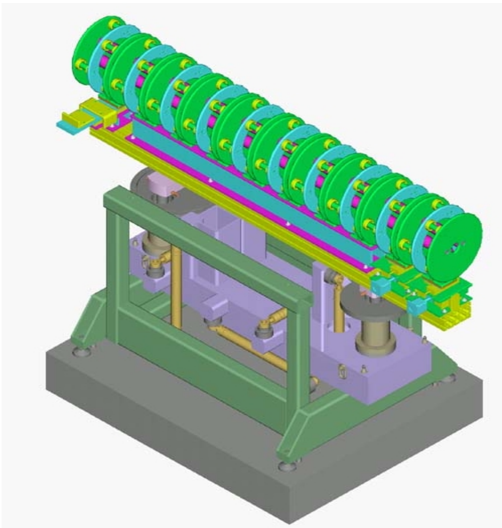


halo generation

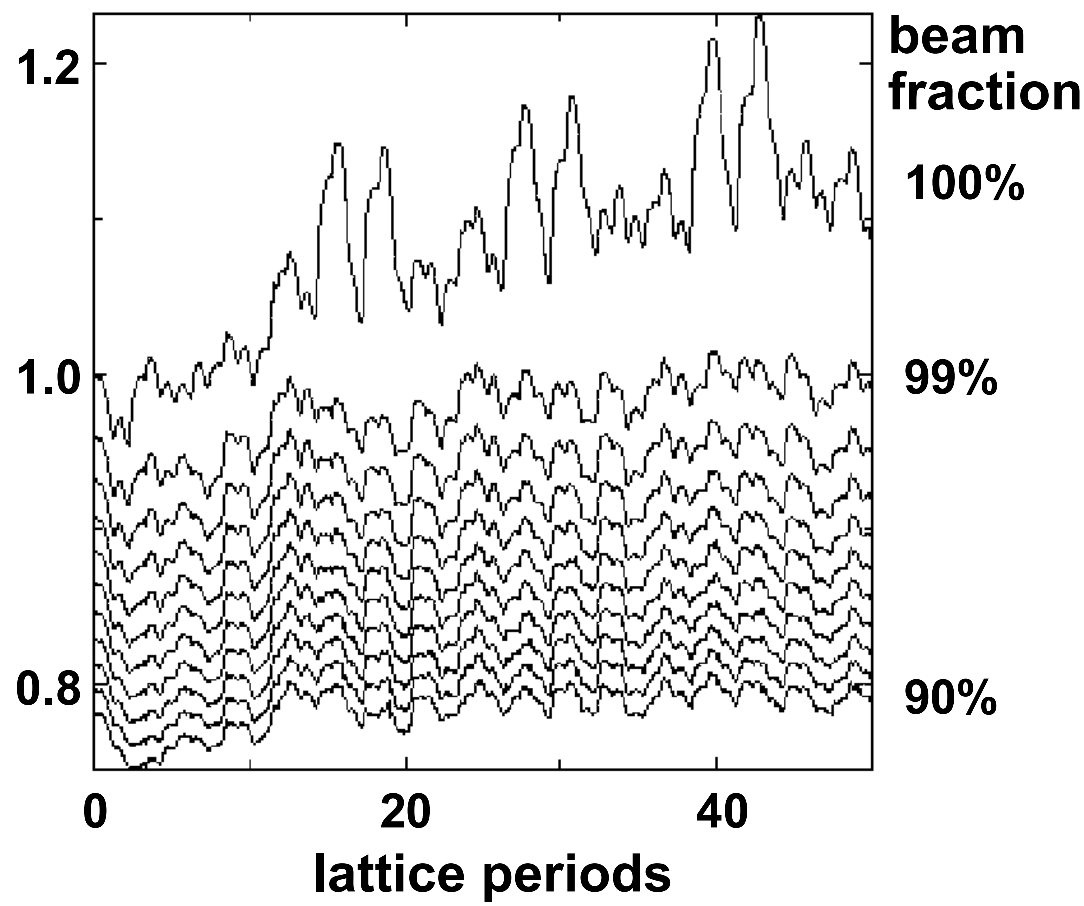


beam propagation in chamber

HCX effort is guided by simulations; here, we show a study of halo induced by beam envelope mismatch



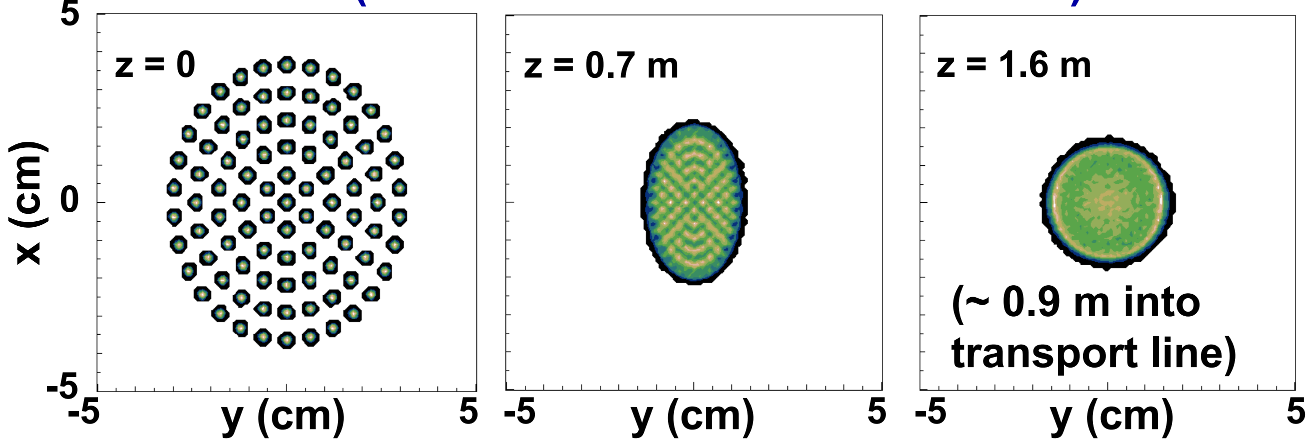
RMS emittance evolution $\varepsilon_x/\varepsilon_{x,\mathrm{initial}}$ vs. beam fraction (32% mismatch amplitude)



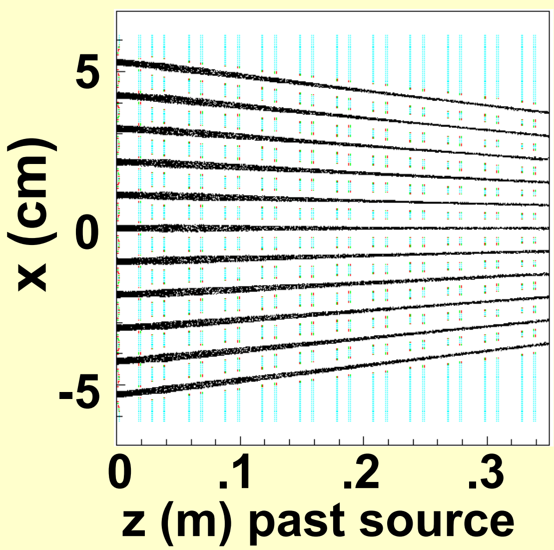
This work established a 10% acceptable mismatch of beam radius for HCX

Simulations of merging-beamlet injector

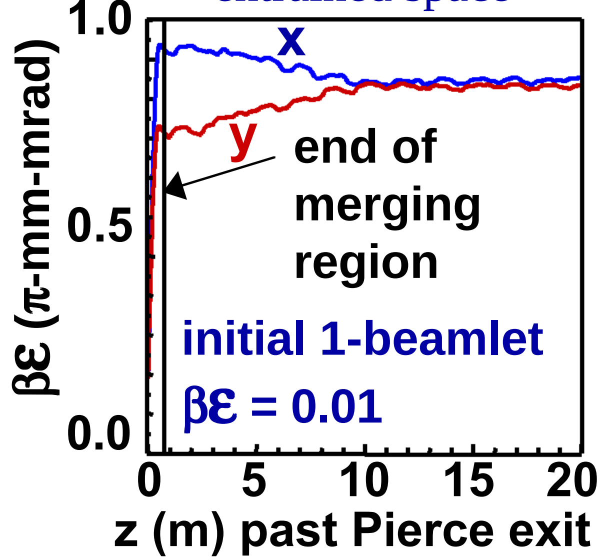
WARPxy: contours of charge density (z relative to Pierce column exit)



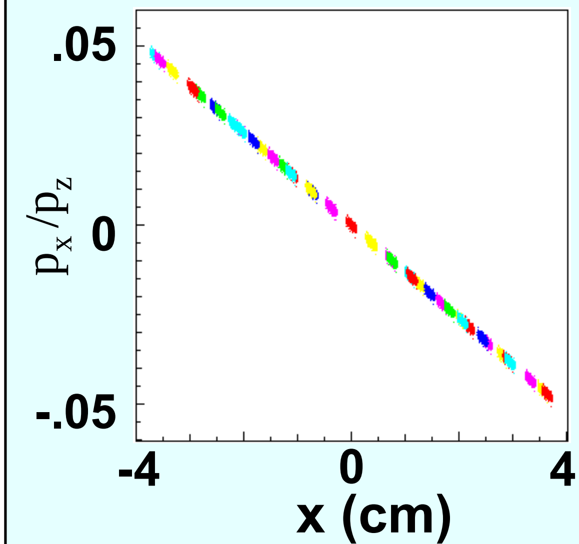
WARP3d: deflections in Pierce column are minimal



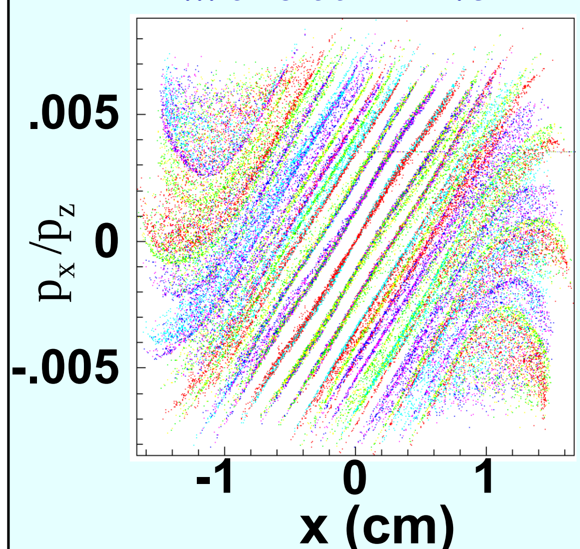
emittance grows due to entrained space



transverse phase space at z = 0 m ...

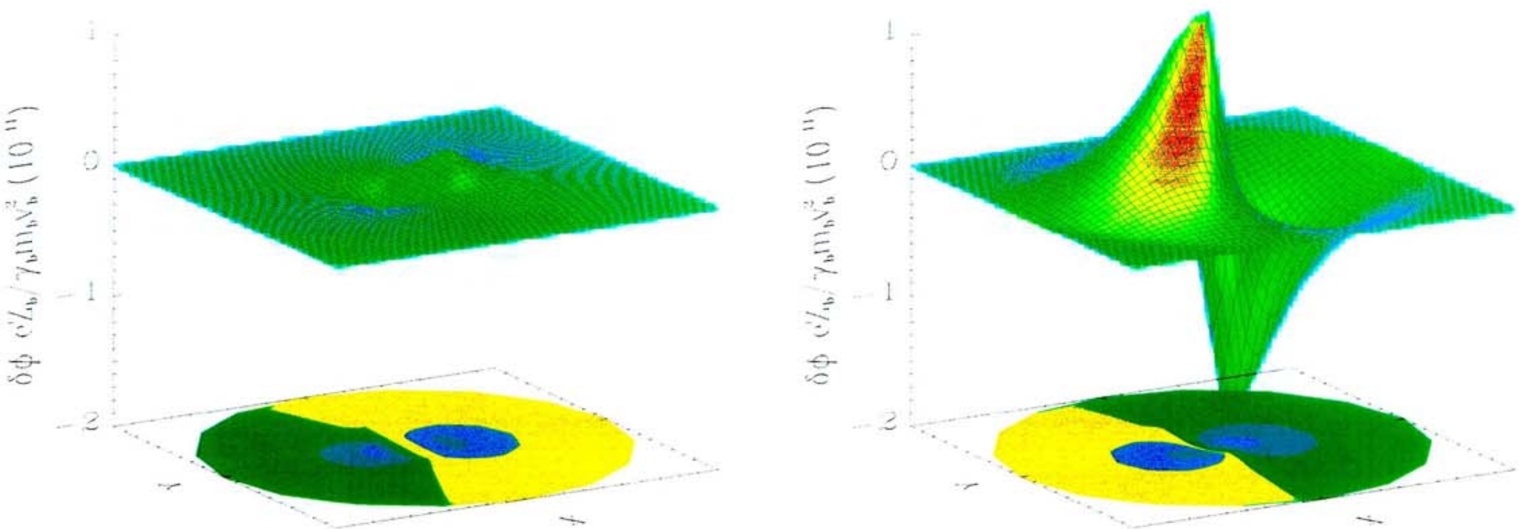


... and at z = 1.6 m



BEST Simulation of Two-Stream Instability

- When a background electron component is introduced with $\beta_e = V_e/c \simeq 0$, the $l = 1$ "surface mode" can be destabilized for a certain range of axial wavenumber and a certain range of electron temperature T_e.



(a) $t = 0$ (b) $t = 200/\omega_{\beta\perp}$

- Linear growth phase shows strong dipole mode structure.

- Two-stream instability can be stabilized by modest axial momentum spread of beam
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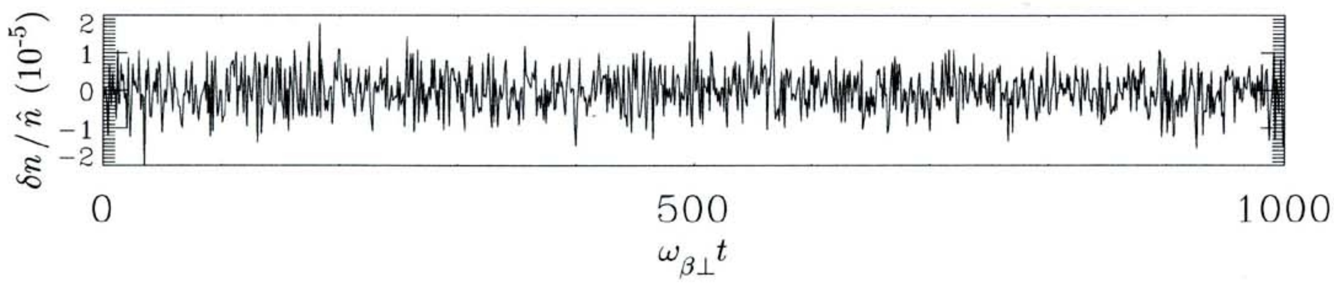
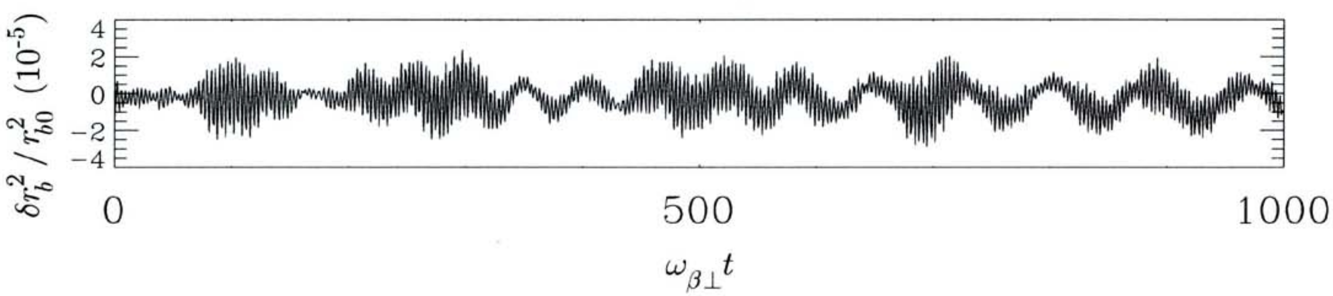
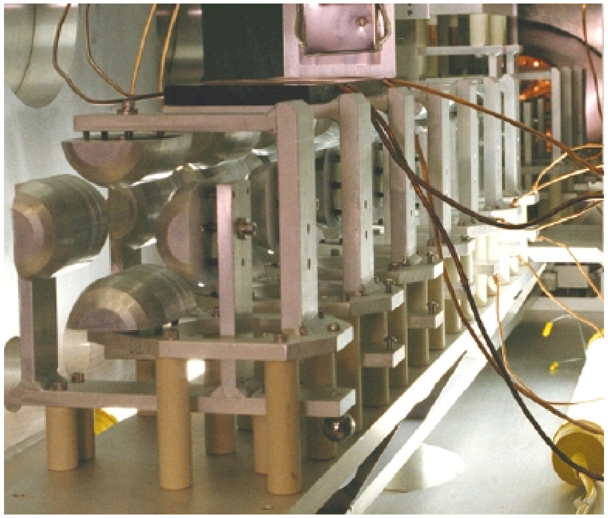
Nonlinear Properties of Thermal Equilibrium Beams



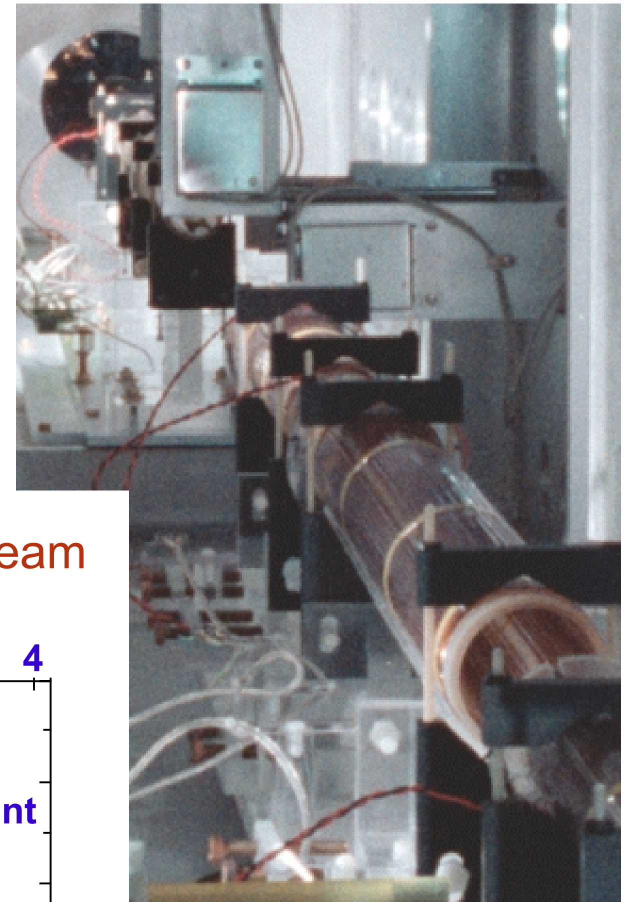


➪ BEST simulation results show that beam propagates quiescently over large distances, which agrees with the nonlinear stability theorem for the choice of thermal equilibrium distribution function.

Final-Focus Scaled Experiment studied effect of neutralizing electrons (from a hot filament) on focal spot size

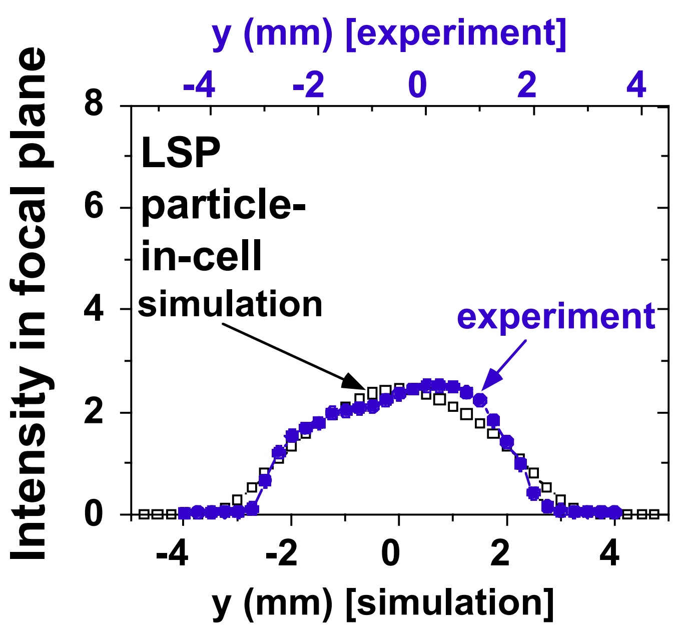


Electrostatic quadrupole lenses for beam set-up

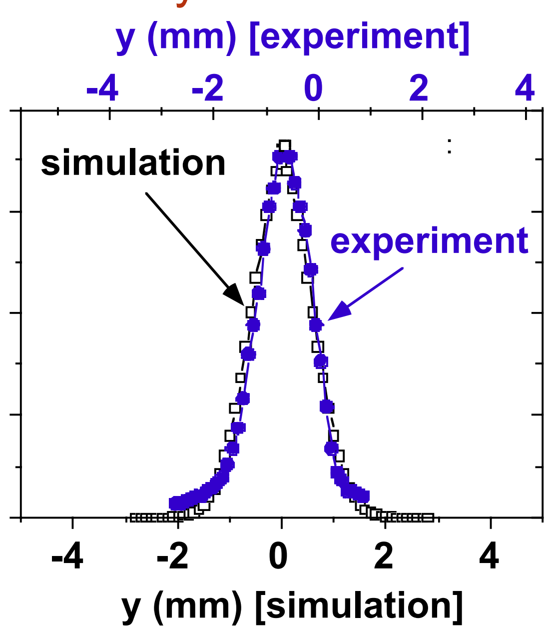


Magnetic quadrupoles for final focusing

Unneutralized beam



Partially neutralized beam



400μA, 160 keV, Cs^+

VNL simulation and theory: selected accomplishments in 2000-2001

A total of 90 VNL publications (articles, proceedings,and books) during 1999-2000

- **The HCX experiment (Phase 1 and 2) dynanical design was intensively simulated to guide planning of the experimental program**
- **A simulation of an initially hollow beam indicated minimal transverse heating as internal modes damped by nonlinear phase mixing, consistent with a non-linear field energy principle**
- **Multiple beam interactions with acceleration models were incorporated into WARP. Resulting growth of the bunching instability was followed into the nonlinear regime, and methods of amelioration were investigated.**
- **Present and future beam source/injector systems were simulated. Optimal designs for maintaining laminar flow (cold beam) were developed for the HCX injector and its upgrade**

VNL simulation and theory: selected accomplishments in 2000-2001 (continued)

- A preliminary study of electron dynamics in magnetic quadrupoles indicated several mechanisms of trapping, potentially leading to an upset of matching ion beam dynamics
- A 3-d multispecies δ f simulation technique was developed for intense beam propagation in periodic focusing systems and used to investigate non-linear evolution of the two-stream instability
- A test-particle model was used to explore halo formation induced by collective mode excitations in intense beams
- A Hamiltonian averaging technique was applied to the Vlasov-Maxwell model of intense beam transport in a periodic focusing system. A non-linear kinetic stability theorem was then applicable, explained quiescent transport over long distances

VNL simulation and theory: selected accomplishments in 2000-2001 (continued)

•The degree of transverse beam heating by non-linear fields during beam splitting was simulated in 2-d. Such an operation now appears to be unattractive unless carried out prior to final beam compression

•Aberrations in final focus were investigated and shown to be consistent with the measured beam spot radius in a 1/10 driver-scale experiment

•Final focus experiments with a neutralized beam were simulated, explaining a dramatic reduction in focal spot radius

•The effects of photoionization, stripping, and direct ionization of flibe gas in ballistic chamber transport were simulated and indicate a high degree of space charge neutralization is easily achieved in realistic fusion chamber conditions

•An extensive upgrade of the 3-d WARP simulation code included new diagnostic, boundary conditions, algorithms, and a capability for self documentation

Theory / simulation has been a significant element of the HIF-VNL's research program

(burdened FTEs include supplies & expenses)	FTE's	$k
LLNL	5.2	1,270
LBNL	3.5 + 1 student	765
PPPL (non-MRC)	2.5 + 1 student	600
Mission Research Corporation	1	240
TOTAL	12.2 + 2 students	2,875

HIF-VNL TOTAL	11,750
Theory / computing fraction of expenditures	24.5%

- Simulation : analytic theory ~ 2 : 1
- In near term, will emphasize bringing in students and postdocs

Our strategic action items are:

- **Aggressively pursue a major role in the Scientific Development through Advanced Computations (SciDAC) initiative**

  Success will greatly accelerate our efforts

- **Develop all the pieces of, and integrate, the required capability via both the SciDAC and the HIF-VNL programmatic effort**

- **Grow our ties to**

  other accelerator computing applications

  - **improve the scientific visibility and status of IFE**
  - **broaden the funding support where appropriate**

  the computational sciences community

  - **contribute our efforts to that broad science**
  - **take advantage of the latest developments**

  university research groups, especially the Computational Engineering Sciences program at UCB

We use a variety of methods and codes

Follow particles (particle-in-cell method)

- **WARP3d and WARPxy (driver)**
- **LSP (chamber & driver; implicit hybrid)**
- **BPIC and BICrz (chamber)**

Follow particles and perturbation to distribution function

- **BEST (chamber & driver)**

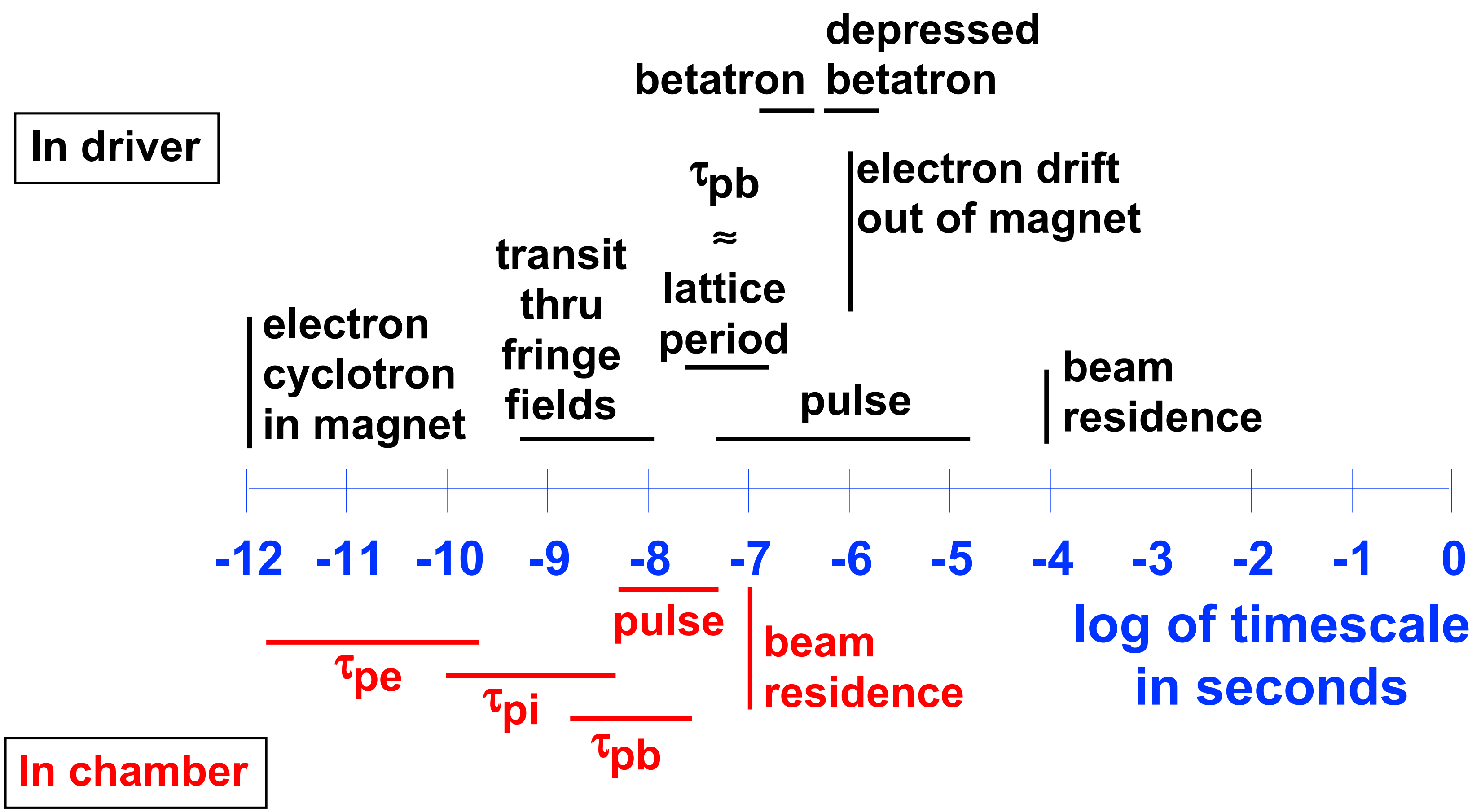
Evolve distribution function on a grid

- **WARP-SLV (driver)**

Evolve moments of distribution function (multi-envelope in x,y; fluid in z)

- **WARP-CIRCE and WARP-HERMES (driver)**

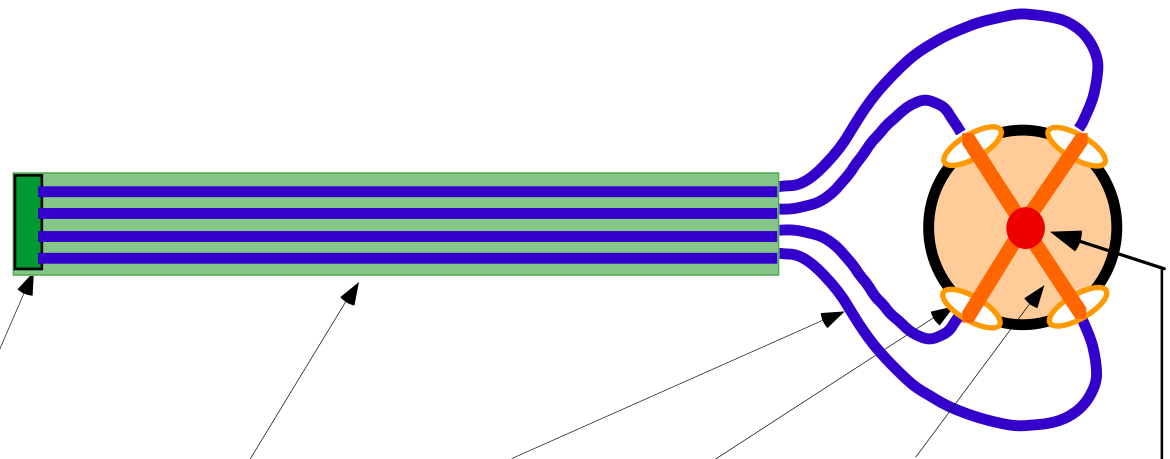
Time scales in driver and chamber span a wide range



Scale lengths range from electron gyroradius in magnet ~.01 mm to $\lambda_{D,beam}$ ~ 1 mm, to beam radius ~ cm, to machine length ~ km's

Vision and Strategy

We will develop an *integrated*, *detailed*, and *benchmarked* source-to-target beam simulation capability

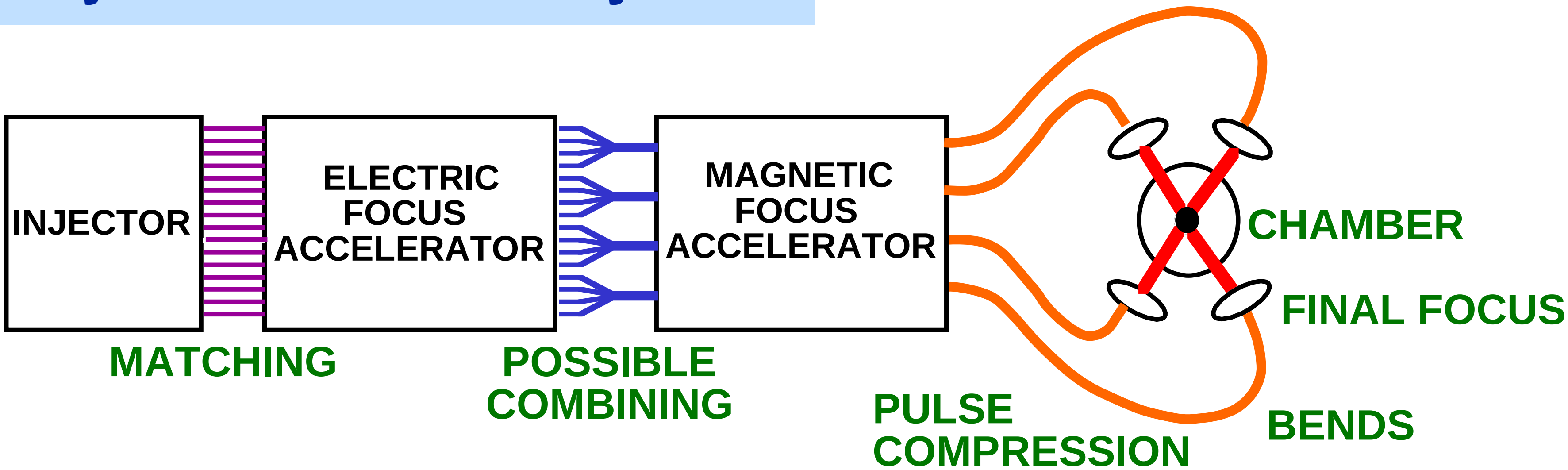


Ion source & injector	Accelerator	Buncher	Final focus	Chamber transport	Target

electrostatic / magnetoinductive PIC and moment models WARP → EM PIC BPIC,LSP → rad - hydro

electromagnetic PIC, LSP | delta-f, BEST | continuum Vlasov WARP

Key issues in an HIF system



In driver:

- quality of injected beam
- ⊥ and λλ emittance growth
- "halo" generation
- instabilities
- stray electrons
- multiple beam effects

In fusion chamber:

- focusing aberrations
- ionization of beam & background
- beam neutralization
- instabilities
- self-magnetic & inductive effects
- multiple beam effects

Backup slide to follow

We must solve difficult problems

In the driver, challenges include:

- efficient but detailed description of applied fields
- time-dependent space-charge limited emission in 3-D
- 10^7 - 10^8 particles, ~ 10^5 steps, > 100 cells in x & y, 1000's in z
- multi-beam effects

Comparisons with experiment can be difficult:

- quadrupole focusing ⇒ sensitivity to diagnostic locations
- diagnostics are (generally) projections of phase space

In the chamber, challenges include:

- complex physics models
- dense plasma; need implicit hybrid model
- large grid, esp. for multi-beam runs; need outgoing wave BC's
- 10^7 - 10^8 particles

Outline

Introduction

Existing capability and current activities

Vision and strategy